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AN EXAMINATION OF THE SUFFICIENCY OF BOTTOM-UP INFORMATION IN SPEECH SEGMENTATION

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1. Introduction

One of the controversial issues in speech perception involves the processes of segmentation and recognition (McQueen, Norris & Cutler, 1994). Segmentation is our division of the speech stream into separate words, and recognition is the point where the word itself is identified. Some theories posit that recognition of words is what allows us to tell where segmentation should take place (Marslen-Wilson, 1987), whereas others think that it is segmentation of the words that facilitates recognition (Norris, 1994). This controversy is part of what divides the main theoretical paradigms of speech perception. Another controversy is over bottom-up and top-down dominance. While it is agreed upon that both top-down and bottom-up information are necessary for perception of everyday speech, theories disagree on which is more important, and whether or not there is interaction between the two streams of data.

There are three main theories of speech perception that are generally used and accepted today. The earliest model is TRACE (McClelland & Elman, 1986) followed by Cohort (Marslen-Wilson, 1987) and most recently, SHORTLIST (Norris, 1994). All of these theories posit that the brain creates a list of candidate words from the speech stream, and that the viability of these candidate words is either strengthened (excited) or weakened (inhibited), depending on how well the candidates match the acoustic signal.

TRACE model of speech perception

Like Cohort and SHORTLIST, TRACE is a competition-based model that involves the excitation and inhibition of different competitors. The TRACE network is made up of interconnected units. Each unit is a hypothesis about what sound is being perceived.

These units are all possible perceptual outcomes. The entire network is called the Trace, because it represents a trace of the analysis of the input at each level, i.e., featural, phonological, and lexical. One of the most controversial factors of TRACE is that it allows for units at the word level to inhibit conflicting units at the phoneme level. For example, if one were to hear the word "giss", it would instead be perceived as "kiss", because the word "giss" does not exist in English. In other words, the top-down lexical information would be dominant, and change the bottom-up phonemic information.

Cohort theory

Cohort theory assumes that the core of speech perception is the recognition of words. The theory breaks this process down into three parts: access, integration, and selection. Access concerns the relationship of the recognition process to the sensory input at the lowest levels, i.e., acoustic phonetic input. Integration concerns the relationship between recognition and higher-level representation of the input. The selection process matches the best word form to the available input. Cohort theory also assumes that the recognition process cannot depend on bottom up information alone. One of the main ideas in the Cohort theory is early selection, which takes advantage of the left to right temporal nature of speech.

SHORTLIST

While TRACE assumes many candidate words are generated from the speech stream, SHORTLIST assumes that only candidates that fit plausibly into the acoustic stream are generated. Hence, for instance, if the phrase "I want to bike" was spoken, the candidates may be something like: *I, want, won, aunt, tube, buy, bike* etc. The incorrect candidates are inhibited when the segmentation and word boundaries make them implausible. As we can see from this information, SHORTLIST posits that it is the process of segmentation that aids in the recognition of words. SHORTLIST hypothesizes that the candidate list is generated using purely bottom-up mechanisms, and also that the bottom-up and top-down streams of information do not interact.

Word segmentation cues

There are several cues that can help listeners decipher where word boundaries occur. Many fall under the category of prosody (Lindfield, Wingfield & Goodglass, 1999). This is a universal feature of language that includes intonation, rhythm, stress, and tone. Although there is great variability in the way these features are expressed cross-linguistically, there is evidence to show that they are useful in helping to segment words.

Phonological cues are also universally available. For example, in English, voiceless stops at the beginning of words are aspirated, whereas intervocalic voiceless stops tend to be flapped. The length of a vowel, although it corresponds with stress in English, is also a cue to segmentation. Other phonological cues have to do with the phonotactics of a language (McQueen, 1998). These are sets of constraints about phoneme combinations that are possible at different points in the word. Phonotactic constraints are useful for showing the listener where a word boundary is not possible (Brent & Cartwright, 1996).

Phonological rules for syllable segmentation may also be used as cues at the word level if the process of syllable segmentation is relevant to word segmentation. Different processes take place in the brain that allow us to distinguish where a syllable begins and ends. The main process of syllabification focused on in this study was Maximal Onset Principle (MOP). This theory states that the initial string of consonants of a syllable must be, as long as possible, within the phonotactic constraints of a language. For example, in a word like *stairway* we would automatically hear the syllable boundary between *stair.way*, because it is against the phonotactics of the language to have a syllable begin (or end) with /rw/.

This study

The focus of this study was on the segmentation of words, and the bottom-up/top-down controversy of speech perception. Under the constraints of SHORTLIST, we predicted that there would be enough bottom-up information for listeners to perceive correct word boundaries in ambiguous situations. The research described above showed that there are several acoustic cues that we can use to segment words. We have tested the perceptual sufficiency of these cues and their relationship to each other in word segmentation.

In order to do this, we examined what happens when there is a competition between two single syllable words that may be segmented in two different ways: either according to MOP or not. For example, when the words *scene* and *eat* are spoken together, MOP would predict that we would hear *see* and *neat* more easily. The primary aim of this study was to discover whether sufficient bottom-up information is provided to override MOP for correct perception of word boundaries. In other words, if it is possible to segment ambiguous words correctly without top-down information, then, bottom-up information would be sufficient for speech segmentation. If all of the words were segmented according to MOP, this would show that maximal onset syllabification points are a strong cue to word boundaries that can be overridden only by the presence of higher-level information.

We have assumed that word recognition takes place through the process of segmentation. Therefore, the paradigm involved only single syllable words (except for one), which would be impossible to recognize before their offset because they would not become unique until after segmentation has taken place. This prevented top-down cues from confounding the experiment, as well as testing whether correct recognition of the word pairs was possible with only bottom-up information.

The goals of the study were: (1) to determine whether or not it is possible to accurately segment a sequence of two words with an ambiguous segmentation point without lexical, semantic or syntactic evidence; (2) to correlate accurate segmentation of ambiguous word pairs with appropriate acoustic and prosodic cues; and (3) to examine whether it is easiest to segment ambiguous word pairs in a way which is consistent with maximal onset syllabification points.

We have hypothesized that there are enough cues available in the data to override Maximal Onset Principle for correct segmentation and recognition of words with ambiguous segmentation points.

2. Methods

This study involved 15 subjects from the University of Victoria, B.C., Canada. This experiment was conducted in two parts. In the first part, five female subjects were asked to read aloud 30 different word pairs. In each word list, there were 20 control, and 10 experimental pairs of words. The experimental pairs, consisted of two words that could be segmented in two different ways, such as *sea neat/scene eat*. The control pairs were two random words in sequence with only one clear segmentation point. Each subject read the same set of words, but two subjects had the experimental word pairs spelled out with segmentation according to Maximal Onset Principle, and the other three had them spelled out in the other possible segmentation. The former procedure was titled list 1, and the latter list 2. The recorded data was analyzed for acoustic segmentation cues, such as intonation, aspiration, pauses and stress.

In the second part of the experiment, 10 subjects were asked to listen to the recorded data, and were instructed to write down the word pairs as soon as they heard them. Results were analyzed for correct or incorrect written responses on each word pair. Statistical analyses were performed to ascertain correlations between acoustic segmentation cues and correct responses. The results were also compared with the results predicted by MOP.

Table 1: Ambiguous word pair list

List 1: Segmented According to MOP	List 2: Not Segmented According to MOP
See neat	Scene eat
Sea table	Seat able
Saw blade	Sob laid
Gray sled	Grace led
Hay track	Hate rack
Law strip	Lost rip
Lay maim	Lame aim
Pack keg	Pack egg
Lay mend	Lame end
My night	Mine Might
Loop straight	Loops trait
May cape	Make ape
Blank street	Blanks treat
Bang keel	Bank eel

3. Results

All words were measured for the variables of pitch change between word boundaries, as well as total length from sound spectrograms, as exemplified in Figures 1 and 2. The pairs were also analyzed for any insertions or reductions between words.

The dotted horizontal lines in the spectrograms above and below (Figures 1 and 2) represent the pitch contour over the word pair. The vertical line represents the approximate word boundary, and the solid horizontal lines represent the intensity. Note that Figure 1 has an insertion between the two words, as well as a drop in pitch. Figure 2 on the other hand has no visible cues to word boundary. There were no instances of segmentation error in either segmentation possibility of this word pair. This suggests that Maximal Onset syllabification was a likely cue for the segmentation of *Lame End* in Figure 2.

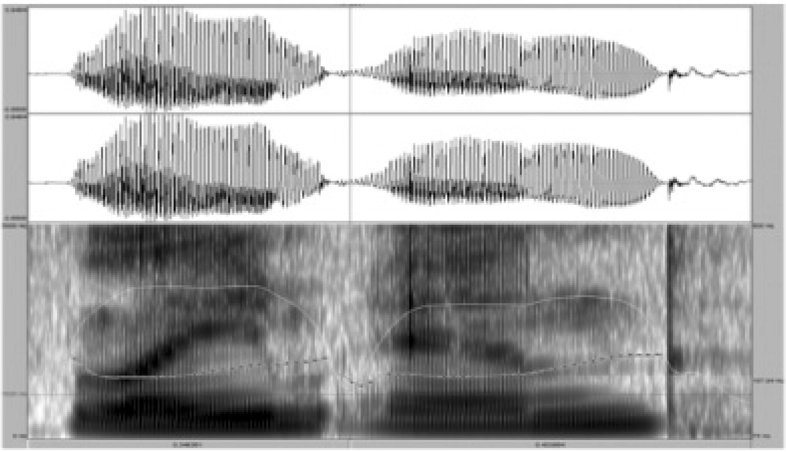

Figure 1. A word pair (lame end) not segmented according to MOP

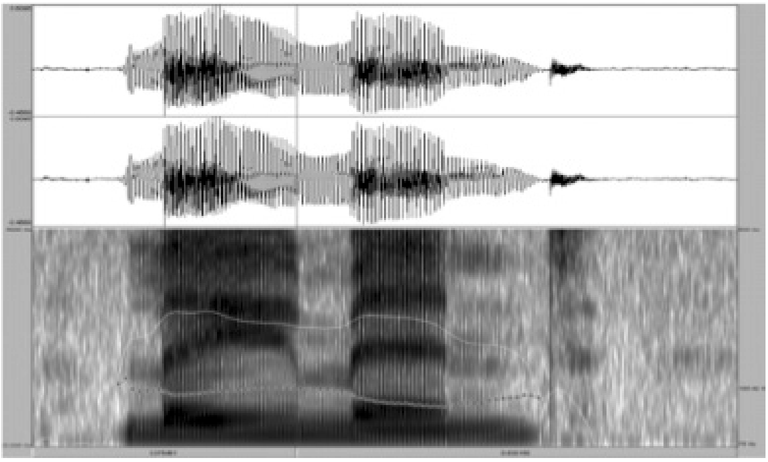

Figure 2: A word pair (lame end) segmented according to MOP

Pitch

Pitch change was measured between the end of the first word, and the beginning of the second, and the raw scores in Hz are shown in Table 2 below.

Table 2: Range and mean of pitch changes in Hz

	Start range (Hz)	End range (Hz)	Difference (Hz)
Low	110.58	80.4	-158.60
High	328.91	246.66	92.03
Average	214.68	194.26	-20.43

Below, Figures 3 and 4 show the frequency scores of the different pitch ratios, and the rate of error for each ratio, respectively.

Figure 3 above shows the number of times that different pitch ratios occurred. The most prevalent ratio was 1.0, which meant there was no pitch change. This occurred 21 times out of the 70 word pairs recorded. A small majority of the pitches were falling pitches (53%). The average pitch ratio for List 2 words was 1.28, while it was only 0.98 for List 1 words, showing a higher prevalence of either pitch raising or flat pitch between the words that were segmented according to MOP.

Figure 4 above shows that 83 % of the segmentation errors occurred at a pitch ratio of one or less. In other words, there was a positive relationship between either a slight rise in pitch or no pitch change, and a segmentation error.

Insertion

In the acoustic data, a total of 33% of the words had insertions between them. All insertions were either a glottal stop, a silence, or a lengthening of the word final consonant, and all occurred with the words in List 2 (not segmented according to MOP). In all cases having insertions, there were no instances of any segmentation errors. This indicates a perfect positive correlation between this acoustic cue and correct segmentation.

Reduction

Ten percent of the acoustic data had reduction cues. All were regarding consonants at the end of the first word. Segmentation was correct in 93% of the perceptual tests involving reduction, and recognition was correct in 64%. This was not significantly better than the average segmentation results. However, reduction appears to have made recognition more difficult, presumably because it created missing pieces in the data, and there was no higher-level information to fill them in.

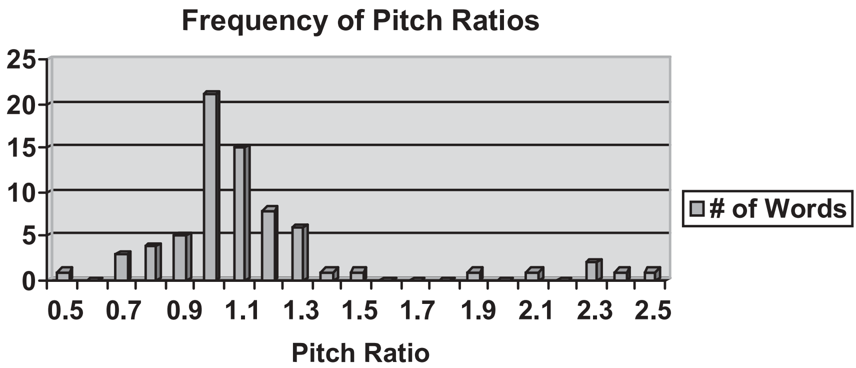

Figure 3: The prevalence of different pitch ratios

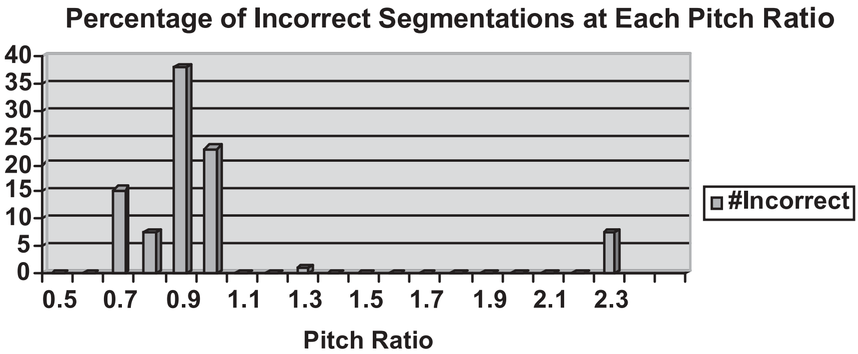

Figure 4: Percentage of incorrect segmentation at each pitch ratio

Length

The length of the recorded word pairs ranged from 0.59 to 1.13 seconds, with an average of .80 seconds, and a standard deviation of .125. There was a large degree of inter-speaker variability, which made it difficult to correlate with the perceptual tests as well as between the List 1 and List 2 words. There was a slight tendency for the List 1 pairs to be shorter. Figure 5 below shows the number of word pairs that took a certain length of time; and Figure 6 shows the errors that occurred at each length.

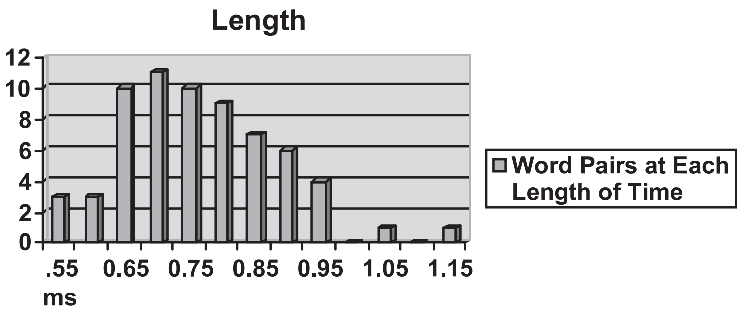

Figure 5: The prevalence of word pairs at each length of time

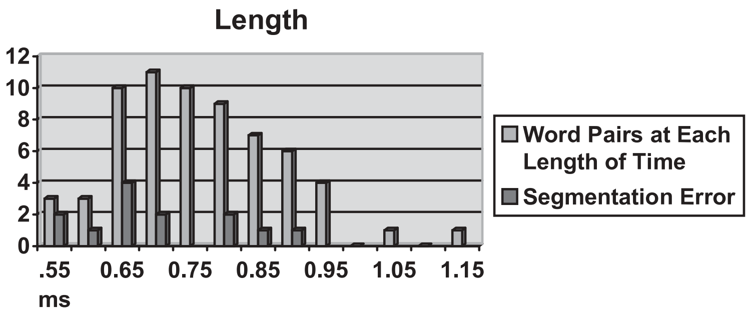

Figure 6: Word segmentation error at each length of time

As the graph shows, all errors occurred when the word pairs were less than .9 seconds.

Perceptual data

There were a total of 140 perceptual responses. Of those responses, only 9.3% of them had segmentation errors, leaving a total of 90.7% correct responses. These results were statistically significant ($p<0.0001$). However, 27.1% of the perceptual tests had recognition errors, leaving only 72.9% perfectly correct words. Although this was still significant, ($p<0.01$), it would not be useful for practical perception purposes in everyday speech. Perception is not efficient if it only occurs correctly 73 percent of the time. An example of correct segmentation and incorrect recognition would be if *Pat Keg* was heard instead of *Pack Keg*, the listener has perceived a separation between two voiceless stops, but has made an error as to the place of the first stop. This occurred in 17.9% of the perceptual tests. All segmentation errors were also counted as recognition errors. Incorrect spellings were not counted as errors. The charts in Figure 7 below show the degree of error for both segmentation and recognition in the perceptual task.

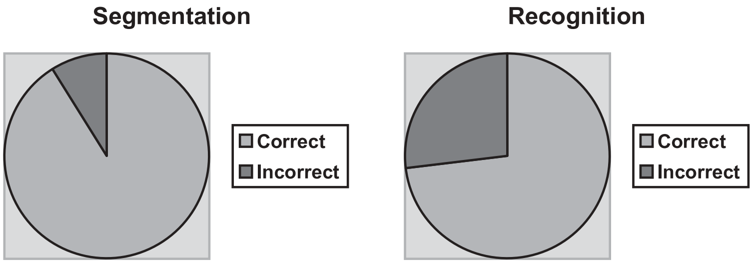

Figure 7: Correct segmentation compared to correct recognition of ambiguous word pairs

Surprisingly, there were more segmentation errors that occurred in the word pairs segmented according to MOP. This was counter to our hypothesis that MOP would be a powerful cue to segmentation. When there was no ambiguity in the perceptual task, scores improved slightly. Ninety seven percent of the control pairs were segmented correctly, and 79% were recognized correctly

4. Discussion

The correlations between incorrect responses and acoustic cues were difficult to measure because of the phonologically variant nature of the word pairs, and also because there were so few mistakes that occurred in the data. Acoustic factors that correlated highly with mistakes may also have been very prevalent in the answers with no segmentation errors. It was likely that more than one cue worked together to create a correct perception of segmentation. Therefore, rather than conclude a universal cue that was used in all segmentation environments, we concluded that different cues are relevant in different contexts. For example, a drop in pitch might be a very useful indicator of a word boundary between two vowels, or a nasal and a vowel. However if there is an insertion of a glottal stop at the end of the first word, then a pitch change to signal the word boundary becomes less necessary. In other words, the prosodic cues used for segmentation interact in a complex way that changes depending on phonological context.

There were, however, some noteworthy correlations. The most obvious of these was the positive correlation between insertion and correct segmentation. One would assume that it is easier to segment words with a slight space between them. Pitch change, specifically, pitch drop also appeared to be a salient cue to word segmentation, as there was a positive relationship between segmentation error, and either a rise, or no drop in pitch.

The recordings of the words in List 1 (segmented according to MOP) had more perceptual segmentation errors than those in List. This was surprising considering our hypothesis that it would be easier to hear words segmented according to MOP. This evidence may question the idea that Maximal Onset syllabification is a strong bottom-up cue that aids in segmentation at the word level.

According to hypothesis one, we proposed that there would be enough bottom-up information for segmentation of ambiguous word pairs. This proved to be true, since over 90% of the word pairs were segmented correctly. Our findings do not discount the usefulness of top-down information in speech perception, but they do give evidence that bottom-up information alone is sufficient for reliable segmentation. This supports the SHORTLIST theory, which claims segmentation is a primarily bottom up process.

Despite the positive results for segmentation, recognition of the correct words was less than perfect. While still adequate, only 72.9 percent of the word pairs were recognized correctly. These findings have significant implications for the Segmentation vs. Recognition controversy. Bottom-up information is sufficient for efficient segmentation, but not recognition. The interaction between these two processes is complex, but the evidence from this study showed that, in our test circumstance, segmentation occurred before, and even aided in, recognition. Therefore segmentation is possible without being dependent on recognition. This is in agreement with the ideas of the SHORTLIST theory.

5. Conclusion

This study examined the nature of bottom-up cues in speech, and their sufficiency in the process of ambiguous word segmentation. There were several phonological and prosodic cues that were discovered in the recorded data, such as pitch change, insertion, and reduction. While it was difficult to determine the exact relationship between the studied cues and word segmentation, the results showed significant evidence that they were sufficient for the segmentation process. Listeners' recognition, however, was not as accurate due to lack of top-down information. It can be concluded from this study that segmentation is a primarily bottom-up process, while recognition relies more on top-down information. These results were in agreement with the predictions proposed by SHORTLIST (Norris, 1994).

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Appendix Table1 ： Data for pitch change，insertion，and reduction

	Segmentation	Length (Sec)	Pitch (Hz)			Insertion	Reduction
			Start	Finish	Change		
1A	Scene Eat	1.05	265.01	197.69	-67.32	Y gl stop	N
1B	Scene Eat	1.13	328.91	230.49	-98.42	Y gl stop	N
1C	Scene Eat	0.80	261.15	227.67	-33.48	Y gl stop	N
2A	See Neat	0.73	210.64	207.63	-3.01	N	N
2B	See Neat	0.70	229.57	228.97	-0.60	N	N
1A	Sob Laid	0.91	201.26	96.72	-104.54	N	N ([b] <)
1B	Sob Laid	0.83	252.93	222.35	-30.58	N	N
1C	Sob Laid	0.88	240.84	189.94	-50.90	N	N
2A	Saw Blade	0.88	186.60	91.40	-95.20	N	N
2B	Saw Blade	0.71	179.71	193.76	14.05	N	N
1A	Seat Able	0.99	229.78	194.65	-35.13	Y gl stop	N
1B	Seat Able	0.83	300.05	205.00	-95.05	Y gl stop	N
1C	Seat Able	0.73	110.58	202.61	92.03	Y gl stop	Y (t)
2A	Sea Table	0.76	219.95	207.12	-12.83	N ([t] asp)	N
2B	Sea Table	0.74	194.29	296.29	2.00	N ([t] asp)	N
1A	Grace Led	0.84	194.38	104.62	-89.76	0.03 s	N
1B	Grace Led	0.73	261.56	204.42	-57.14	0.03 s	N
1C	Grace Led	0.65	228.21	195.26	-32.95	0.45 s	N
2A	Grey Sled	0.84	193.32	204.13	10.81	N	N
2B	Grey Sled	0.60	187.65	201.63	13.98	N	N
1A	Hate Rack	1.10	189.94	183.97	-5.97	0.10 s	N
1B	Hate Rack	1.00	249.18	218.00	-31.18	0.06 s	N
1C	Hate Rack	1.13	228.66	220.56	-8.10	0.05 s	Y t-gl st
2A	Hay Track	0.80	185.03	175.06	-10.03	N	N
2B	Hay Track	0.68	228.00	220.56	-7.44	N	N
1A	Lost Rip	0.85	184.85	80.40	-104.45	N	Y t-0
1B	Lost Rip	0.74	264.85	106.79	-158.06	N	N
1C	Lost Rip	0.76	278.23	207.00	-71.23	N	N
2A	Law Strip	0.84	183.54	233.7	50.16	N	N
2B	Law Strip	0.61	171.45	165.43	-6.02	N	N
1A	Lame Aim	0.93	200.00	180.88	-19.12	Y gl stop	N
1B	Lame Aim	0.82	218.45	96.2	-122.25	Y gl stop	N
1C	Lame Aim	0.73	244.01	222.57	-21.44	?	N
2A	La Maim	0.80	191.39	190.72	0.67	N	N
2B	Lay Maim	0.65	173.03	177.05	4.02	N	N
1A	Pack Egg	0.89	213.02	186.80	-26.22	Y gl stop	N
1B	Pack Egg	0.80	245.82	197.58	-48.24	Y gl stop	N
1C	Pack Egg	0.68	245.14	217.88	-27.26	Y gl stop	Y [k]
2A	Pack Keg	0.87	200.61	200.73	0.12	N	Y [k]
2B	Pack Keg	0.59	138.08	187.75	49.67	N	N
1A	Lame End	0.95	217.61	180.77	-36.84	Y gl stop .04	N
1B	Lame End	0.80	220.46	183.42	-37.04	Y gl stop .05	N
1C	Lame End	0.75	238,07	177.05	-49.00	N	N
2A	Lay Mend	0.84	186.76	185.35	-0.41	N	N
2B	Lay Mend	0.67	185.25	185.24	-0.01	N	N
1A	Mine Night	0.93	232.3	211.11	-21.19	Y [n]	N
1B	Mine Night	0.89	225.16	213.90	- 11 .26	Y [n]	N
1C	Mine Night	0.82	249.63	235.69	-13.94	Y .13s	N
2A	My Night	0.87	192.65	192.1	-0.55	N	N
2B	My Night	0.67	178.96	180.11	1.15	N	N
1A	Loops Trait	0.91	251.86	241.99	-9.87	0.10 s	N
1B	Loops Trait	0.75	249.66	246.66	-3.00	0.05 s	N
1C	Loops Trait	0.73	267.08	226.40	-40.68	0.06 s	N
2A	Loop Straight	0.94	185.48	178.36	-7.12	Voicing [d]	N
2B	Loop Straight	0.68	219.79	174.88	-44.19	?	N
1A	Make Ape	0.78	214.86	90.19	- 124.67	Y gl stop .11	N
1B	Make Ape	0.74	237.08	201.15	-35.93	Y gl stop .13	N
1C	Make Ape	0.80	229.35	212.69	-16.66	Y gl stop .10	N
2A	May Cape	0.98	176.27	209.87	33.60	N	N
2B	May Cape	0.70	195.78	201.48	5.70	N	N
1A	Blank Street	0.83	213.16	217.71	4.55	N	N
1B	Blank Street	0.71	237.33	232.12	-5.60	N	N
1C	Blank Street	0.60	237.38	224.58	-12.80	N	Final [t]
2A	Blanks Treat	0.98	162.75	216.70	53.95	0.10 s	N
2B	Blanks Treat	0.70	152.88	216.32	63.44	N	N
1A	Bank Eel	0.76	194.37	177.21	-17.16	Y gl stop	N
1B	Bank Eel	0.67	222.47	180.45	42.02	Y gl stop .07	N
1C	Bank Eel	0.67	173.29	225.15	51.86	Y gl stop .07	N
2A	Bang Keel	0.86	181.95	204.74	22.79	Y 0.1 s	N
2B	Bang Keel	0.70	188.48	203.32	14.84	N	N